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Gastric emptying during exercise: effects of heat stress and hypohydration

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Summary. To determine the effects of acute heat stress, heat acclimation and hypohydration on the gastric emptying rate of water (W) during treadmill exercise, ten physically fit men ingested 400 ml of W before each of three 15 min bouts of exercise (treadmill, ~50% $\dot{V}_{O_2max}$) on five seperate occasions. Stomach contents were aspirated after each exercise bout. Before heat acclimation (ACC), experiments were performed in a neutral (18°C), hot (49°C) and warm (35°C) environment. Subjects were euhydrated for all experiments before ACC. After ACC, the subjects completed two more experiments in the warm (35°C) environment; one while euhydrated and a final one while hypohydrated (−5% of body weight). The volume of ingested water emptied into the intestines at the completion of each exercise bout was inversely correlated ($P<0.01$) with the rectal temperature ($r=-0.76$). The following new observations were made: 1) exercise in a hot (49°C) environment impairs gastric emptying rate as compared with a neutral (18°C) environment, 2) exercise in a warm (35°C) environment does not significantly reduce gastric emptying before or after heat acclimation, but 3) exercise in a warm environment (35°C) when hypohydrated reduces gastric emptying rate and stomach secretions. Reductions in gastric emptying appear to be related to the severity of the thermal strain induced by an exercise/heat stress.

Key words: Thermal strain – Heat acclimation – Treadmill exercise – Fluid replacement – Stomach secretions

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Introduction

During exercise, core temperature increases in proportion to the metabolic rate of the activity (Neilsen 1938). In order to minimize the rise in core temperature, skin blood flow increases and sweat is secreted to dissipate the metabolically released heat. During prolonged exercise in a hot environment, sweat rate (and thus body water loss) can exceed 1.0 l · m^{-2} · h^{-1} (Adolf 1947; Costill et al. 1970). If not adequately replaced by fluid ingestion, this body water deficit will result in an increase in both thermal and cardiovascular strain, thereby reducing heat loss and exercise performance (Sawka et al. 1984a).

It has generally been assumed that fluid ingested during exercise/heat stress will be readily absorbed by the gut. In a recent study however, Owen et al. (1986) found an increase in the gastric residue recovered following treadmill exercise performed in a warm [35°C, 20%–50% relative humidity (r.h.)] as compared with a neutral (25°C, 20%–50% r.h.) environment. Although gastric emptying was assessed from only a single residue obtained immediately following 2 h of exercise and fluid ingestion, these findings do suggest that acute exercise/heat stress may reduce gastric emptying, possibly limiting fluid replacement.

It is well established that heat acclimation reduces the thermal and cardiovascular strain associated with a given exercise-heat stress (Rowell 1983). This raises the question that, if acute exercise/heat stress reduces gastric emptying, does heat acclimation attenuate this reduction? In contrast, the thermoregulatory advantages associated with heat acclimation are compromised in individuals performing exercise in the heat when hypohydrated as compared with euhydrated (Sawka et al. 1983). Both the separate and combined effects of heat acclimation and hypohydration on the gastric emptying rate of water in individuals performing exercise in the heat have not been previously addressed.

The purpose of the present study was to examine the influence of exercise heat stress on the gastric emptying rate of water in unacclimated, heat acclimated and hypohydrated subjects. We hypothesized that, compared with exercise in a neutral environment (18 °C), acute heat stress (both 35 and 49 °C) would reduce gastric emptying while heat acclimation would attenuate this reduction. Further, we hypothesized that the added thermoregulatory strain associated with hypohydration would impair gastric emptying during an exercise heat stress as compared with euhydrated conditions. The findings of this study have direct implications for hydration and rehydration procedures to be employed by athletes, workers and military personnel engaged in physical activity.

Methods

Subjects. Ten men volunteered for this study after being informed of the requirements and possible risks associated with this research. One week before experimental testing, each subject's maximal oxygen uptake ($\dot{V}O_{2max}$) was determined from a progressive treadmill test (Sawka et al. 1984a). In addition, nude body mass was obtained every morning throughout the study. Mean body mass was used to establish base-line data that represented euhydration for each subject. The characteristics (mean ± SE) of the subjects were age 19.3 ± 0.4 yr, height 1.76 ± 0.23 m, mass 66.1 ± 1.4 kg, and $\dot{V}O_{2max}$ 57.9 ± 0.8 ml · kg^{-1} · min^{-1}. The study was conducted in Natick, Mass., from late March to early May in order to minimize any effects of natural heat acclimatization.

Experimental design. All experiments were completed following a 12–16 h overnight fast. Upon reporting to the test chamber, the subjects were intubated with a number 14 French, Levine gastric tube through the nasal passage. Each subject ingested 200–300 ml of water to facilitate the intubation procedure and to aid in the subsequent removal of the fasting gastric residue. Once intubated, the subjects completed a 10 min warm-up treadmill run (2.68 m · min^{-1}, 0% grade). This procedure has previously proven effective in eliminating any reduction in the initial gastric emptying rate that may occur due to an overnight fast or lack of physical activity (Neufer et al. 1986). After the warm-up exercise, stomach contents were removed via aspiration with a 50 ml syringe. The nasogastric tube was moved systematically within the stomach during aspiration to insure complete evacuation of the gastric residue.

Water served as the test drink for all trials. The drinks were administered cold at ~5 °C and contained 25 mg · l^{-1} of phenol red, a nonabsorbable marker (Schedl 1966). The design for all experiments was the same. After completing the warm-up exercise, the subjects ingested 400 ml of water and performed 15 min of treadmill exercise (~50% $\dot{V}O_{2max}$). Immediately post exercise, gastric contents were aspirated. A second 400 ml of water was then ingested and the process repeated with each subject completing a total of three 15 min exercise bouts per experiment. It is important to note that there is considerable interindividual variation in gastric emptying. However, the reliability of this method for repeated measures within the same individual has previously been reported (Costill and Saltin 1974). In addition, the reliability coefficient for 10 subjects in the present study performing 4 identical gastric emptying trials (2.68 m · s^{-1}, 0% grade, 18 °C) was 0.83. During all experiments, rectal temperature was monitored via a thermistor inserted 100 mm beyond the anal sphincter. If rectal temperature exceeded 39.5 °C at any time during the experiments and/or acclimation sessions (described below), testing of that subject was discontinued for the day and the subject was removed to a cool environment. Heart rate (b · min^{-1}) was obtained via radiotelemetry and recorded during the 5th and 10th min of each 15 min exercise bout. All gastric emptying experiments were separated by at least one day of rest.

Each subject completed five experiments. Our primary intent was to elicit a gradation in the degree of thermal strain experienced by the subjects during each of the experiments. Before acclimation, the subjects completed three experiments: one experiment (N-UN) in a neutral environment (18 °C, 20% r.h.), a second experiment (H-UN) in a hot environment (49 °C, 20% r.h.), and a third experiment (W-UN) in a warm environment (35 °C, 20% r.h.). The subjects were euhydrated for all experiments performed before heat acclimation. After acclimation, the subjects completed two more experiments in the warm environment (35 °C, 20% r.h.): one experiment (W-ACC) while euhydrated, and a final experiment (HY-ACC) while hypohydrated by 5% of body weight. Due to the severity of the heat stress during experiment H-UN, only 7 of the 10 subjects were able to complete two of the three exercise bouts before achieving a rectal temperature of 39.5 °C. No subject completed the third exercise bout. In addition, several subjects complained of severe gastric distress. In view of these responses, no experiments were performed in the hot environment (49 °C, 20% r.h.) after heat acclimation.

The heat acclimation program consisted of two 50 min treadmill exercise (~50% $\dot{V}O_{2max}$) bouts in the heat (49 °C, 20% r.h.) separated by 10 min of rest for 7 consecutive days. During the acclimation sessions, rectal temperature and HR were monitored continuously. The subjects wore gym shorts, T-shirts, and tennis shoes during all testing.

Approximately 24 h before the hypohydration experiments (HY-ACC), the subjects voluntarily restricted their food and fluid consumption. In addition, during the afternoon of the day before experiment HY-ACC, the subjects performed light intensity exercise in a hot (49 °C) environment to dehydrate by 5% of their baseline body weight. Subjects achieving a weight reduction greater than 5% were allowed an appropriate amount of fruit juices. The subjects rested during the night in a comfortable environment. The following morning subjects were weighed, provided with water if sufficiently underweight, instrumented, and instructed to sit quietly for 30 min. A small (3 ml) blood sample was obtained (venipuncture) from an arm vein for subsequent plasma hematocrit, hemoglobin, total protein, and osmolality determination. An identical procedure for blood sampling was also carried out before experiment W-ACC.

Physiological and biochemical analysis. Heart rates were determined from electrocardiograms obtained with bipolar (CM5) chest electrodes and radiotelemetered to an oscilloscope-cardiotachometer unit (Hewlett-Packard). Oxygen uptake measurements were performed with an automated system (Sensormedic Horizon MMC).

Blood samples obtained before the euhydrated (W-ACC) and hypohydrated (HY-ACC) experiments were placed in tubes containing 72 USP units of lithium heparin. Each blood sample was analyzed in triplicate for hemoglobin (Hemoglobinometer, Coulter Electronics), hematocrit (micro-centrifugation), plasma protein (refractometry, American Optical), and osmolality (Osmette A, Precision Systems).

Following aspiration, the volume of gastric residue was recorded and an aliquot of the residue stored at 5 °C. Before analysis, gastric residues were centrifuged at 4 °C to separate any mucous within the residue. A 1 ml sample of the supernatant was then placed in 5 ml of a water boric acid buffer. The pH of the buffered residue solution was adjusted to 9.2 and the optical density measured spectrophotometrically at 560 nm. The ratio of the optical density of the residue to the optical density of the original drink provided quantification as to the dilution of the original drink by gastric secretion (Schedl 1966). In addition, the volume (ml) of ingested water emptied into the intestine (original drink emptied) and the volume of stomach secretion added to the residue was calculated. Gastric emptying rate was estimated by dividing the volume of original drink emptied by the total time of each exercise bout (15 min). The percent of original drink emptied was determined by dividing the volume of original drink emptied by the volume of water consumed (400 ml).

Statistical analysis. Statistical comparisons were made using a repeated measures analysis of variance. If significant main effects were indicated, Tukey's critical difference was calculated to locate significant differences at the $P<0.05$. All data are presented as mean ± SE.

Results

Rectal temperature and heart rate

Rectal temperatures increased significantly during exercise for all experiments (Fig. 1). Exercise in a warm environment (35 °C) in the unacclimated state (W-UN) elicited a modest rise in rectal temperature that was greater than experiments N-UN and W-ACC during the second and third exercise bouts. The rectal temperature responses in the warm environment (W-ACC) following heat acclimation were not different from responses observed during experiment N-UN. When subjects were hypohydrated (HY-ACC), rectal temperature was higher than experiments N-UN and W-ACC by the end of the first exercise bout and remained elevated over experiments N-UN, W-UN, and W-ACC during the final two exercise bouts. Two subjects were forced to withdraw from the hypohydration experiment (HY-ACC) due to illness resulting in an N of 8 for experiment HY-ACC. The largest increase in rectal temperature occurred during experiment H-UN. By the end of the first exercise bout, rectal temperature during H-UN was higher than during experiments N-UN, W-ACC and W-UN and, during

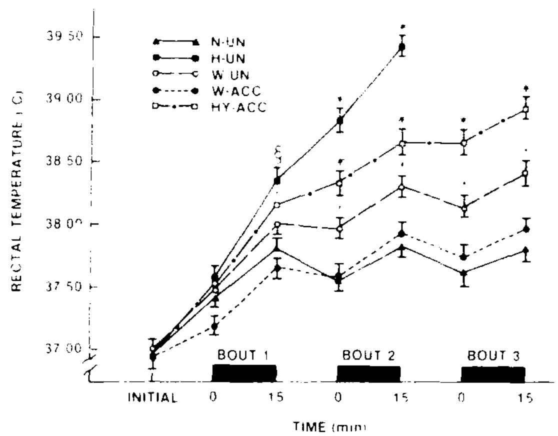

Fig. 1. Rectal temperature (°C) values (mean ± SE) for experiments N-UN (18 °C, unacclimated), H-UN (49 °C, unacclimated), W-UN (35 °C, unacclimated), W-ACC (35 °C, acclimated), and HY-ACC (35 °C, 5% hypohydrated and acclimated). * Significantly different ($P<0.05$) from all other experiments. † Significantly different from experiments N-UN and W-ACC. § Significantly different from N-UN, W-ACC and W-UN

the second exercise bout, greater than all other experiments.

Table 1 presents the heart rate data for the three exercise bouts during each experiment. Heart rates during exercise in the hot environment (H-UN) were significantly higher than all other experiments for bouts 1 and 2. In addition,

Table 1. Heart rate during exercise

Experiment	Bout 1		Bout 2		Bout 3	
	5th min	10th min	5th min	10th min	5th min	10th min
N-UN	146 ± 3	150 ± 3	145 ± 3	151 ± 3	146 ± 3	152 ± 3
H-UN ($n=7$)	171* ± 9	187* ± 7	196* ± 5	201* ± 6		
W-UN	153 ± 4	160† ± 4	159† ± 4	164† ± 4	159† ± 6	164† ± 5
W-ACC	151 ± 3	157 ± 4	153 ± 3	159† ± 3	160† ± 4	160† ± 3
HY-ACC ($n=8$)	158† ± 6	170† ± 6	167† ± 6	173† ± 6	170† ± 5	178† ± 5

Values are mean ± SE ($n=10$) for heart rate ($b \cdot min^{-1}$) during the 5th and 10th min of each 15 min treadmill exercise session for experiments N-UN (neutral environment, 18 °C), H-UN (hot environment, 49 °C preacclimation), W-UN (warm environment, 35 °C preacclimation), W-ACC (warm environment, 35 °C post acclimation), and HY-ACC (5% hypohydrated, 35 °C, post acclimation). * Significantly ($P<0.05$) different from all experiments. † Significantly different from experiment N-UN. ‡ Significantly different from experiment N-UN and W-UN

Table 2. Characteristics of gastric residues

Experiment	Bout 1		Bout 2		Bout 3		~ Emptying rate (ml · min⁻¹)
	ODE	SS	ODE	SS	ODE	SS	
N-UN	300.8	58.9	331.1	41.7	314.0	37.1	21.0
	± 21.3	± 6.7	± 18.6	± 7.1	± 24.2	± 5.7	± 1.4
H-UN	219.6*	48.0	196.1†	33.9			13.9†
(n = 7)	± 24.3	± 3.1	± 35.9	± 2.3			± 2.0
W-UN	263.5	38.3	278.9	33.6	307.9	25.7	18.9
	± 15.9	± 4.9	± 13.9	± 6.5	± 19.5	± 4.5	± 1.1
W-ACC	278.9	42.0	324.3	25.8	316.1	29.2	20.4
	± 13.9	± 4.5	± 16.0	± 5.2	± 17.5	± 4.9	± 1.1
HY-ACC	241.9*	21.6*	229.3†	17.3*	235.8†	13.9*	15.7†
(n = 8)	± 26.2	± 2.8	± 27.8	± 3.7	± 29.3	± 3.3	± 1.9

Values are mean ± SE ($n = 10$) for the the volume (ml) of original drink emptied (ODE) from the stomach to the intestine and the volume (ml) of stomach secretions (SS) added to the gastric residues during each 15 min exercise session for experiment N-UN (neutral environment, 18° C), H-UN (hot environment, 49° C preacclimation), W-UN (warm environment, 35° C preacclimation), W-ACC (warm environment, 35° C post acclimation), and HY-ACC (5% hypohydrated, 35° C post acclimation). Also presented is the approximate average emptying rate (ml · min⁻¹) during each experiment
* Significantly different ($p < 0.05$) from experiment N-UN. † Significantly different from experiments N-UN, W-UN, and W-ACC

heart rates during experiment HY-ACC were greater than during experiments N-UN and W-UN. Exercise in the warm environment (experiments W-UN and W-ACC) also elicited slightly greater heart rate responses as compared with experiment N-UN.

Following 7 days of heat exposure, final rectal temperature values during acclimation sessions were significantly lowered from 39.06 ± 0.16° C on day 1 to 38.19 ± 0.11° C on day 7. Final exercise HR values were significantly decreased from 155 ± 4 $b \cdot min^{-1}$ on day 1 to 136 ± 3 $b \cdot min^{-1}$ on day 7. Rectal temperatures and HR were not significantly different between days 5, 6 and 7, and, as such, heat acclimation was accepted as being complete.

Gastric emptying: acute exercise-heat stress. Table 2 presents the volumes of original drink emptied and the corresponding average gastric emptying rates during experiments N-UN, H-UN and W-UN. The volume of original drink emptied averaged 315.3 ± 21.3 ml for the three exercise bouts during experiment N-UN, corresponding to a mean emptying rate of 21.0 ± 1.4 ml · min⁻¹. In contrast, the volumes of original drink emptied were less during experiment H-UN as compared with N-UN in bout 1 and experiments N-UN and W-UN in bout 2, corresponding to a gastric emptying rate during experiment H-UN of *13.9 ± 2.0 ml · min⁻¹*. The volume of original drink emptied during experiment H-UN, expressed as a percentage of the volume ingested (400 ml), averaged only 52% as compared with 79% during experiment N-UN. The gastric emptying responses during experiment W-UN were intermediate to experiments N-UN and H-UN, being less than experiment N-UN only during the second exercise bout (Table 2).

Gastric emptying: heat acclimation and hypohydration. All ten subjects achieved the prescribed level of hypohydration before experiment HY-ACC. Table 3 gives the resting values of blood constituents when the subjects were euhydrated and 5% hypohydrated. Values for hemoglobin, hematocrit, osmolality and plasma protein were greater

Table 3. Blood constituents in the euhydrated and 5% hypohydrated state

Hydration state	Blood parameter			
	Hb g · 100 ml⁻¹	Hct %	Osm mosmol · l⁻¹	PP g · 100 ml⁻¹
Euhydrated	14.2	43.9	280	7.1
	± 0.3	± 0.6	± 1	± 0.1
Hypohydrated	16.8*	50.0*	287*	8.8*
	± 0.5	± 1.2	± 2	± 0.3

Values are mean ± SE ($n = 10$) for hemoglobin (Hb), hematocrit (Hct), osmolality (Osm) and plasma protein (PP), from blood samples obtained 30 min before experiments W-ACC (euhydrated) and HY-ACC (5% hypohydrated). * Significantly ($P < 0.05$) different from corresponding euhydrated value

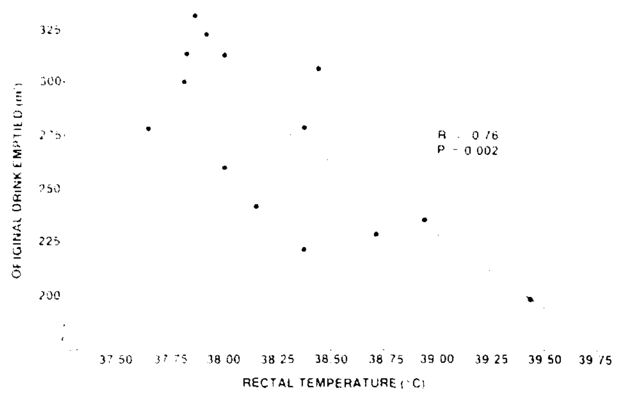

Fig. 2. Correlation of final exercise rectal temperatures (°C) recorded during the 10th min vs the corresponding volume (ml) of original drink emptied for each exercise session

before experiment HY-ACC as compared with W-ACC. These data are in agreement with previously reported changes of blood constituents following a similar dehydration protocol (Sawka et al. 1984a).

As shown in Table 2, heat acclimation did not significantly influence the volume of original drink emptied during any of the exercise bouts, resulting in an average emptying rate of 18.9 ± 1.1 ml · min^{-1} and 20.4 ± 1.1 ml · min^{-1} for experiments W-UN and W-ACC, respectively. In contrast, the volume of original drink emptied during the second and third exercise bout of experiment HY-ACC was reduced as compared with experiment W-UN and W-ACC. The emptying rate during the final two bouts of exercise of experiment HY-ACC averaged 15.5 ± 1.9 ml · min^{-1}. This corresponds to an average 58% of the original drink emptied during experiment HY-ACC as compared with an average 81% for the final two exercise bouts of experiment W-ACC.

Table 2 also presents the mean values for the volume of fluids added by the stomach (stomach secretions) during each experiment. Stomach secretions were consistently reduced during experiment HY-ACC, being lower than all experiments during bout 1, and experiment N-UN during bouts 2 and 3.

To determine the relationship between gastric emptying and the thermoregulatory strain, data from all experiments was pooled. A negative correlation ($r = -0.76$, $P < 0.01$) was found between the final exercise rectal temperature and the corresponding volume of original drink emptied for each exercise bout (Fig 2).

Discussion

This study demonstrates that gastric emptying is markedly reduced in individuals performing treadmill exercise in a hot (49°C) as compared with neutral (18°C) environment. Moreover, gastric emptying is also reduced in individuals (heat acclimated) performing exercise in a warm (35°C) environment when hypohydrated (−5% of baseline body weight) as compared with euhydrated. The process of fluid replacement is a function of both the rate at which gastric contents empty from the stomach and the rate at which fluids are absorbed from the small intestine. Our results suggest that the first step (gastric emptying) in this process is impaired relative to the thermoregulatory demand of an exercise/heat stress (Fig. 2).

Previous studies have reported that thermoregulation and exercise performance can be maintained in the heat when individuals ingest water during the activity (Costill et al. 1970; Gisolfi and Copping 1974; Pitts et al. 1944). Although gastric emptying was not measured, the authors (Costill et al. 1970; Gisolfi and Copping 1974; Pitts et al. 1944) attributed these findings to the effectiveness of the ingested water in minimizing water losses incurred by dehydration. Despite these previous reports regarding the overall benefits of fluid replacement, the results of the present study demonstrate that gastric emptying rate is greatly reduced when exercise is performed in a hot (49°C) environment. Owen et al. (1986) recently reported a marked increase in the volume of gastric residue recovered immediately following 2 h of exercise in the heat (35°C) as compared with a comfortable environment (25°C). In the present study, however, exercise at a similar ambient temperature (35°C, experiment W-UN) did not consistently influence the gastric emptying rate as compared with exercise in the neutral environmental (18°C). This apparent discrepancy may be explained by the fact that, in the study by Owen et al. (1986), relative humidity ranged from 30%–50% near the end of each 2 h exercise (65% $\dot{V}_{O_{2}max}$) bout. In the present study, however, relative humidity was maintained at 20% and exercise intensity at 50% $\dot{V}_{O_{2}max}$. Consequently, the greater thermal strain experienced by their subjects (86) resulted in an increase in rectal temperature from ~38.50 to ~39.50°C during the final hour of exercise, similar to the responses observed in our subjects during experiment H-UN (Fig. 1).

The mechanism by which acute heat stress impairs gastric emptying rate during exercise remains open to speculation. Exercise in the heat may exert a direct inhibitory effect on the contractile activity of the stomach. Increased intragastric pressure, generated by contractions of the proximal region of the stomach, is believed to be the primary mechanism for emptying of liquids (Minami and McCallum 1984). This contractile activity within the stomach is thought to be controlled through the vagal system and/or the release of various gut hormones, both of which inhibit proximal gastric contractions. Increased activity of either of these mechanisms during acute exercise/heat stress would thereby limit gastric emptying. In addition, plasma β-endorphins have also been reported to delay gastric emptying by decreasing the gastric contraction rate (Konturek 1980). However, it should be noted that increases in plasma β-endorphins are generally reported to occur after, and not during exercise (Farrell 1985; Goldfarb et al. 1987). Another possible mechanism for the observed reductions in gastric emptying may be related to alterations in splanchnic blood flow. Exercise in the heat is characterized, among other physiological responses, by a redistribution of cardiac output away from the splanchnic region, most likely due to increased sympathetic nervous activity (Rowell 1983; Rowell et al. 1987). A reduction of splanchnic blood flow could compromise plasma fluid uptake in the intestine, resulting in an excess intestinal fluid volume, thereby causing a reduction in gastric emptying.

In contrast to our hypothesis, heat acclimation was not accompanied by an enhanced gastric emptying rate in experiment W-ACC as compared with W-UN (Table 2). However, it is important to note that gastric emptying during exercise in the warm environment (35 °C) before heat acclimation (experiment W-UN) was not different from experiment N-UN. Thus, the relatively mild additional heat strain during experiment W-UN was insufficient in eliciting a consistent decrement in the gastric emptying rate. It is possible that in conditions where heat stress is sufficient to impair gastric emptying (compared with temperate conditions), heat acclimation may attenuate this impairment.

In additon to impairing thermoregulation, hypohydration reduced stomach secretions and decreased gastric emptying rate (Table 2). Gastric secretion is primarily regulated by both neural (parasympathetic innervation to the stomach) and hormonal (gastrin) mechanisms. Thus, a reduction in stimulation of either mechanism during experiment HY-ACC may have accounted for the reduced stomach secretions. Alternatively, reductions in stomach secretions may have been related to the hypohydration mediated increase in osmolality and the associated decrease in blood volume (Table 3). It is possible that such a response resulted in a defense of plasma volume concomitant with a reduced blood flow within the secretory cells of the stomach, thereby decreasing stomach secretions. It seems likely that the reduction in gastric emptying observed during experiment HY-ACC was a function of the thermal strain induced by hypohydration and exercise/heat stress. As previously discussed, alterations in gastric contractile activity and/or splanchnic blood flow may have accounted for this reduced gastric emptying rate.

It may be argued that, in the present study, the reductions in gastric emptying observed during experiments H-UN and HY-ACC were a function of the relative metabolic cost of the activity. Maximal oxygen uptake has been reported to decrease during exercise in a hot (49 °C) environment (Sawka et al. 1985) and/or warm environment when hypohydrated (Craig and Cummings 1966; Sawka et al. 1984a). Thus, it seems likely that the subjects in the present study were working at a higher relative %$\dot{V}_{O_{2max}}$ during experiments H-UN and HY-ACC. However, attempting to establish a cause and effect relationship between gastric emptying and relative %$\dot{V}_{O_{2max}}$ during an exercise/heat stress is misleading. The reduction in $\dot{V}_{O_{2max}}$ during exercise in the heat is most likely due a competition between central and peripheral circulation for a limited blood volume, resulting in an inability to maximally increase cardiac output (Sawka et al. 1984a). The physiological mechanism responsible for the increase in the relative cost of submaximal exercise performed in the heat, therefore, is probably a direct result of the increased thermal strain. Likewise, it seems reasonable to assume that the reductions in gastric emptying were primarily mediated by the greater demand upon the thermoregulatory system during experiments H-UN and HY-ACC, with the increase in %$\dot{V}_{O_{2max}}$ being a secondary response. In support of this concept, the volumes of original drink emptied were negatively correlated with the corresponding rectal temperatures obtained during each 15 min exercise bout (Fig. 3). Thus, it appears that gastric emptying rate during a given exercise is dependent upon the severity of the thermal strain induced by an individual's hydration state and/or the surrounding environmental conditions.

With this in mind, our results emphasize the need to ingest fluids during industrial, athletic and/or military activities before the development of dehydration and high core temperatures. Under such conditions where the demand upon the thermoregulatory system is increased (experiment HY-ACC), gastric emptying rate decreases thereby limiting the ingested fluid's effectiveness in defending plasma volume and replacing depleted body water stores. These findings are consistent with Adolf's (1) early ideas concerning forced rehydration. Thirst is known to be a poor index of body water requirements such that ad libitum water intake during exercise in the heat results in an incomplete replacement of body water losses (Adolf 1947; Pitts et al. 1944). In addition, as little as a 2% reduction in body weight induced by dehydration elevates core temperatures during an exercise-heat stress as compared with euhydration (Sawka et al. 1984a). Thirst (and therefore voluntary fluid intake) is probably not perceived until similar levels of body water deficit (2%) have been incurred (Adolf 1947). Further, this delay in rehydration (voluntary dehydration) is greater in individuals when unacclimated to exercise in the heat (Eichna et al. 1945; Greenleaf et al. 1983). Thus, individuals experiencing the greatest thermoregulatory strain during an activity will often incur the largest levels of voluntary dehydration. Consequently, gastric emptying rate will decrease and fluid gains to the body will be minimized. Therefore, forced hydration during the early stages of an exercise/heat stress is important, not only to avoid voluntary dehydration, but to maximize the bioavailability of the ingested fluids.

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